Nutrient Concentrations and Trophic State of Small Patagonian Andean lakes

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ABSTRACT

We analyzed nutrient, chlorophyll, and ionic concentrations in 17 lakes along a strip of land located in the rainy Andes Mountains and the ecotone with the dry Patagonian steppe, from 36 to 44° S latitude. Most of the sampled lakes had the ionic composition of Andean lakes and showed ultraoligotrophic conditions, while a few with the ionic composition of Patagonian Plateau lakes showed higher nutrient concentrations. Chlorophyll was correlated to P and N concentrations, but chlorophyll /TP ratio was lower than reported in previous worldwide surveys. A lithology dominated by igneous rock together with the remoteness and pristine character of the basins contribute to the oligotrophic status of the lakes. Two other factors appear to be important in maintaining the oligotrophic condition. Andisols, allophanic soils developed over volcanic ash deposits in the rainy areas, have large P retention capability and therefore decrease the load of P to the lakes. Natural dense *Nothofagus* spp. forests, with a geographical distribution coincident with that of the andisols, are efficient mechanisms for nitrogen retention through nitrogen resorption from senescent leaves.

INTRODUCTION

Although Argentina comprises hundreds of lakes of different sizes, it was not until the 1980s that a first survey of the hydrochemistry of 103 lakes distributed all around the country became available (Quirós 1988). Further studies based on nutrient and trophic state lakes distinguished two main districts within the Patagonia region; the rainy Andean Patagonia, characterized by deep oligotrophic lakes, and the dry Patagonia Plateau, characterized by shallower, more saline, and higher trophic state lakes (Quirós and Drago 1999).

The dominant climatic element in Patagonia is the persistence and strength of the westerly winds, which reach spring and summer maxima. The moisture is mostly removed by the orographic effect of the Andes Mountains, creating wet conditions in the western slope and valleys and a steep precipitation gradient towards the eastern Patagonian Plateau. Dense stands of *Nothofagus* spp. deciduous forests lie in the wet parts of the gradient, while a transition of scattered grass and shrub communities characterize the ecotone areas (Mazzarino *et al.* 1998a).

The larger Andean Patagonian lakes have been recognized as former glaciers forming fjord like systems with eastward moraines (Hutchinson 1957). Tectonic and aeolic lakes are common in the closed depressions of the extra-Andean plateau (Iglesias de Cuello 1982). Dominant rock types are granites and diorites in the Andes and basalts in the Plateau (Drago and Quirós 1996). Vulcanism has had a strong influence and lakes located on basins filled with volcanic ashes are frequent in the ecotone between the forest and steppe (Marcolini *et al.* 1988). Soil composition of the Patagonian landscape is diverse with prevailing andisols on the west while mollisols and aridisols are dominant in the plateau (Del Valle 1998).

Baigún and Marinone (1995) considered 54 Patagonian lakes and noted that due to the strong prevailing winds Patagonian lakes have deeper thermoclines than the northern hemisphere cold temperate lakes. Theses authors pointed out that the vast majority of the Patagonian lakes were cold polymictic, departing from current lake classification in that only high mountain, small, and sheltered lakes undergo winter freezing. They also found that mean depth was the best univariate predictor of chlorophyll concentration for their heterogeneous data set, and total organic nitrogen was a better predictor of chlorophyll concentration than total phosphrous. In turn, Pedrozo *et al.* (1993) studied the nutrient concentration in lakes and streams in the Andean Patagonia around Bariloche (41° 05'S, 71°20"W), reporting low nutrient concentrations and suggesting that N limitation was widespread.

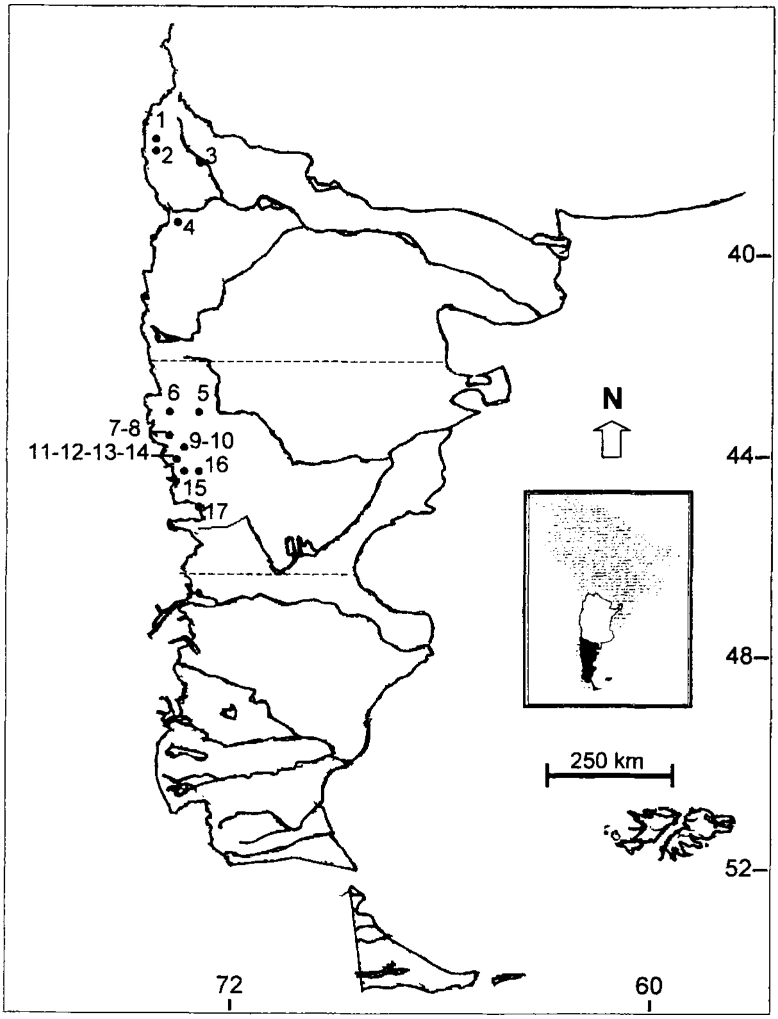

Figure 1. Location of the sampled lakes in Patagonia. The lakes are: Epulaufquen (1),Vacalaufquen (2), Palao (3), Pulmari (4), Pellegrini (5), Lezama (6), Zeta (7), Terraplén (8), Guacho (9), Engaño (10), Vilches (11), Escondido (12), Pava (13). Constancio (14), Pico (15), Torres (16), and Azul (17).

Although these previous studies contributed basic limnological knowledge of Patagonian lakes, they were focused mostly on moderate to large waterbodies (> 20-100 km^2), ignoring potential differences among large and small lakes. The water chemistry of a multitude of small lakes remains largely unknown, despite that several small lakes have limnological relevance as they are located in still undisturbed areas or exhibit ecological interest as being located in the ecotone between the Andes and the plateau.

We analyzed nutrient concentrations and trophic state of the small lakes located in the rainy Andes Mountains and its boundary with the dry Patagonian plateau.

METHODS AND MATERIALS

Samplings were conducted in summer on February 1999 and early March 2001 in 17 lakes (Fig. 1). Temperature and dissolved oxygen were measured *in situ* on the surface and bottom with a YSI 51B recorder and pH with an Orion 250A pH meter. Water samples were immediately filtered through Whatman GF/C filters. Chlorophyll *a* concentration was spectrophotometrically measured after acetone extraction of the filters following APHA (1998). Ca^{2+} and Mg^{2+} (atomic absorption), Na^+ and K^+ (flame photometry), HCO_3^- (Gran titration), SO_4^{2-} (turbidimetry) and Cl^- ($AgNO_3$ titration) were determined following APHA (1998). Tot-P (Andersen 1979) and Kjeldahl N (APHA 1998) were measured in unfiltered water samples fixed in the field with H_2SO_4. The basin/lake surface ratio and the percentage of each basin covered by forests were estimated through planimetry over satellite images 1: 100,000.

Pearson correlations (Sokal and Rohlf 1979) were calculated among all measured parameters in the lakes by using Statistica software.

RESULTS

Mean lake area was 248 hectares, and mean depth was 11 m (Table 1). The lakes had small fetch and were mostly round to elongate shaped with a shoreline development of 1-2. All lakes contained high oxygen concentrations and did not exhibit variations with depth nor thermal stratification (except Lezama Lake). A large proportion of the lakes (76%) showed similar ionic composition, and conductivity was low with HCO_3^- and Ca^{2+} being the main ions (Table 2). These lakes include Guacho, Pava, Azul,

Table 1. Morphometric characteristics of the sampled lakes. Z_{mean}: mean depth; Z_{max}: maximum depth; Alt.: altitude; SDI: shore development index; B/L: ratio between basin and lake area; %F: proportion of each basin covered by forests.

Lake	Latitude	Longitude	Z_{mean} (m)	Z_{max} (m)	Area (ha)	Fetch (m)	Alt. (m)	SDI	B/L	%F
Group 1 lakes										
Lezama	42°26'37"	71°28'45"	36.4	75.0	635	6,966	750	1.95	3	100
Pulmari	39°06'49"	71°06'12"	11.7	19.0	172	2,850	1000	1.86	50	90
Azul	44°25'11"	71°19'16"	18.0	36.1	120	1,920	1250	1.45	6	90
Guacho	43°48'39"	71°29'16"	16.4	28.2	423	5,750	1250	1.90	7	80
Vacalaufquen	36°53'16"	71°05'46"	22.5	39.8	205	3,470	1550	1.66	16	60
Pava	44°10'38"	71°30'16"	5.6	12	35	1,159	700	1.47	10	20
Engaño	43°51'35"	71°31'04"	5	16.7	314	2,420	1000	1.23	9	90
Epulaufquen	36°49'31"	71°04'52"	27.4	41.4	319	3,280	1450	1.36	14	60
Escondido	44°16'49"	71°29'06"	5.6	8.5	26	1,085	800	2.17	6	20
Pico	44°19'14"	71°29'39"	11.4	22	709	4,895	800	1.95	4	10
Terraplén	42°59'06"	71°31'00"	11.6	19.2	267	2,230	750	1.19	5	26
Vilches	44°07'44"	71°34'20"	3.7	5.5	197	2,447	700	1.35	6	26
Constancio	44°16'40"	71°31'12"	5	12	74	1,674	650	1.60	5	14
Group 2 lakes										
Torres	44°07'40"	71°05'59"	2.7	9	101	1,657	800	1.34	91	8
Pellegrini	42°29'40"	71°23'24"	9.6	15.0	516	4,795	500	1.51	76	0
Palao	36°55'57"	70°18'53"	2.5	3.6	57	1,080	2200	1.11	40	0
Zeta	42°53'22"	71°20'56"	6.4	10.0	66	1,654	850	1.44	19	0

Pulmari, Lezama, Engaño, Vacalaufquen, Pico, Epulafquen, Escondidlo, Terraplén, Vilches, and Constancio and are termed Group 1 lakes by us. The remaining four lakes are arbitrarily termed Group 2 lakes; they include Torres, Pellegrini, Zeta, and Palao.

Group 1 lakes showed distinctively low chlorophyll concentrations accompanied by comparatively low TN and TP concentrations (Fig. 2). Torres Lake and Pellegrini Lake represented different patterns exhibiting the largest ratio between basin and lake surface and had higher conductivity than Group 1 lakes. Nevertheless, the proportion of each ion remained the same as in Group 1 lakes. Zeta Lake and Palao Lake showed the highest conductivities and different ionic composition. Pellegrini Lake and Zeta Lake showed higher nutrient and chlorophyll concentrations than Group 1 lakes.

Chlorophyll concentration was correlated with TP ($r=0.84$; $P<0.01$) and TN ($r=0.75$; $P<0.05$). If Pellegrini Lake and Zeta Lake were excluded from analysis, the chlorophyll concentration was significantly correlated with TP ($r= 0.82$, $P<0.05$) but not with TN. Total nitrogen and total phosphorus were correlated with each other ($r= 0.66$; $P<0.01$) and also with the ratio between basin and lake area ($r= 0.65$ and 0.51 respectively, $P<0.05$), with conductivity ($r= 0.84$ and 0.91, $P<0.05$), with HCO_3^- ($r= 0.94$ and 0.93, $P<0.05$), and with water transparency ($r= -0.77$ and -0.71, $P<0.05$). Furthermore, TN was correlated with pH ($r= 0.57$, $P<0.05$) and inversely with the percentage of forest cover at each basin ($r=-0.81$, $P<0.01$)(Fig. 3).

Table 2. Limnolgical variables in the sampled lakes.

Lake	O_2 mg l^{-1}	Secchi m	Conductivity µS cm^{-1}	pH	TN µg l^{-1}	TP µg l^{-1}	Chl µg l^{-1}	HCO_3^- mg l^{-1}	SO_4^{2-} mg l^{-1}	Cl^- mg l^{-1}	Ca^{2+} mg l^{-1}	Mg^{2+} mg l^{-1}	Na^+ mg l^{-1}	K^+ mg l^{-1}	N/P
Group 1 lakes															
Lezama	9.5	11	94	8.3	168	7	0.7	55	<0.5	1.2	8.3	3.0	7	1.3	24
Pulmari	11	6.5	60	6.9	187	37	1.1	9	17.4	9	4.6	1.4	2.2	0.8	5
Azul	11	6	31	6.3	196	19	0.9	10	1.8	2.9	2.2	0.8	2.2	0.5	10
Guacho	9	12	51	6.4	227	26	0.4	11	9.0	4.6	2.8	0.5	1.2	0.4	9
Vacalaufquen	10	5.5	50	6.4	216	84	1.1	56	44	5.1	3.5	0.9	1.7	0.8	3
Pava	10.2	10	39	7.9	235	8	0.2	19	<0.5	1.2	3.0	1.0	3	0.9	29
Engaño	10	7	34	5.9	294	28	0.9	15	2.2	3.9	3.8	0.8	1.5	0.8	11
Epulafquen	11	6	41	6.1	388	47	1.5	13	1.8	6.1	4.3	0.9	1.6	0.7	8
Escondido	10	11	34	7.5	434	8	0.7	16	<0.5	1.6	2.4	0.9	2.7	0.6	54
Pico	10.5	7	49	7.6	514	6	0.4	22	<0.5	1.1	4.6	1.1	3	0.6	86
Terraplén	10	6	84	7.0	740	47	0.9	67	1.2	2.6	8.1	4.6	7.6	1.4	16
Vilches	9.7	3.7	60	7.7	732	10	0.4	34	<0.5	1.0	4.8	1.8	4.5	1.1	73
Constancio	10.5	5.5	46	7.8	944	10	0.6	24	<0.5	1.0	4.0	1.2	3	0.9	94
Group 2 lakes															
Torres	9.5	5	140	8.6	1025	17	0.3	74	<0.5	0.5	12.9	4.7	9.2	2.0	60
Pellegrini	9.2	0.7	119	9.1	1754	91	77	63	3.2	0.1	14.0	3.0	7.2	2.1	19
Palao	8	3	776	8.2	758	56	1.1	111	258	7.1	56.5	33	37	8	14
Zeta	9.5	1	389	8.8	2218	126	22	189	8.2	4.0	29.4	11	30.5	6.0	18

DISCUSSION

Lack of thermal stratification is a consequence of lake shallowness and the strong wind prevailing in the area and is consistent with previous observations that Patagonian lakes only stratify when mean depth is greater than about 25 m (Baigún and Marinone 1995). Based on the ionic composition, Group 1 lakes represent typical Andean environments, while Zeta Lake and Palao Lake comprised Patagonian Plateau lakes, with higher ionic concentration and higher proportion of Na and SO_4^{2-}, which are concentrated by evaporation and washed from the surrounding soils. Although different from each other, these features are found in the arid Patagonia Plateau, where deflation basins produced by aeolic erosion are frequent (Iriondo 1989). In turn, Torres Lake and Pellegrini Lake represent transitional environments with increased conductivity but otherwise with the same composition as the Andean Patagonian lakes.

Following the criteria of Vollenweider (1976) further developed by OECD (1982) and Ryding and Rast (1992), 13 lakes were considered as ultraoligotrophic, two as oligotrophic, and two as eutrophic. Quirós and Drago (1999) described the Andean Patagonian lakes as ranging from ultraoligotrophic to oligotrophic, while the Patagonia Plateau lakes range from mesotrophic to eutrophic. According to nutrient and ionic composition, most of the studied lakes represented typical Andean Patagonian lakes, while a few were similar to the lakes of the Patagonia Plateau. Both Pedrozo *et al.* (1993) and Quirós and Drago (1999) interpreted the low nutrient content of the lakes as a consequence of the igneous bedrock and remoteness of the basins from populated areas. They also emphasized that water depth was a determinor of trophic state. In turn, Baigún and Marinone (1995) claimed that mean depth was the main component determining the trophic status of Patagonian lakes.

In Patagonia where point sources are negligible, dilution of non-point nutrient loads in the deepest lakes explains the low nutrient concentration. The finding that large and deep glacial lakes with small cultural impact were oligotrophic is not surprising. The observed correlation between TP and chlorophyll concentration in the small study lakes was consistent with previous observations (OECD 1982, Ryding and Rast 1992), which assumed a universal P limitation of phytoplankton growth. Nevertheless, the present set of lakes depict a lower Chl/TP ratio than often quoted in the literature. Our results are consistent with those of Baigún and Marinone (1995) whose work was mostly based on moderate to large lakes. In turn, Soto and Stockner (1996) reported lower chlorophyll concentration for a given amount of TP in Araucanian lakes (Chile) compared with Canadian lakes. They suggested that Chilean lakes were N-limited while the Canadian lakes were P-limited. However, N fixing blue-green algae were not observed in Chilean lakes. Wurtsbaugh *et al.* (1985) reported N limitation for phytoplankton growth together with P limitation for N fixation in the high altitude Andean Titicaca Lake (Bolivia-Perú).

In the present study only four of the 17 lakes showed TN/TP similar to or lower than 7. Nitrogen limitation, although not uncommon, does not seem widespread. We

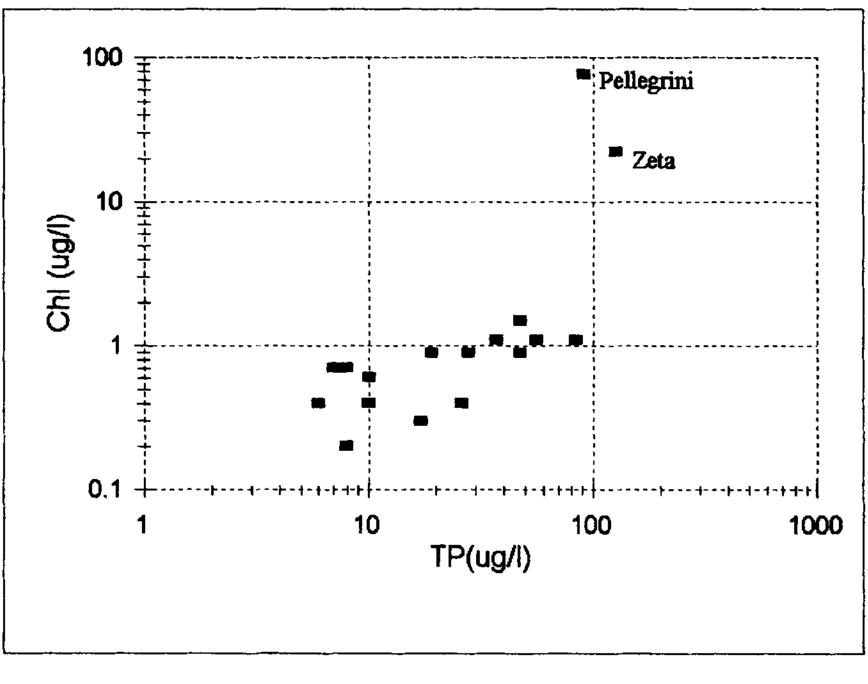

Figure 2. Total phosphorus-chlorophyll relationship in the studied lakes.

noted that Pellegrini Lake and Torres lake occupied the bottoms of extended valleys perpendicular to the ecotonal strip. The basins, much larger than those of the Group 1 lakes, lack forests and sheep farming was the main activity. Overgrazing is not uncommon and may enhance runoff-related nutrient loads. The two shallowest lakes, Torres Lake and Palao Lake, were colonized by dense stands of submersed macrophytes and Secchi depths were higher than mean depths. These lakes showed a comparatively high N and P contents together with low chlorophyll concentration. In lakes with dense macrophyte development, the total chlorophyll content is likely to be larger in the periphyton than in the phytoplankton.

In the Andean Mountains were andisols are dominant, shallow lakes would depict a comparatively large detrital TP concentration derived from bottom re-suspension by wind action. The high sorption capacity of the allophanic material might, however, reduce soluble reactive phosphorus availability, thus explaining the low Chl/TP ratio. The correlation between TN and the proportion of the basin covered by forest may reflect the influence of the terrestrial vegetation on nitrogen export from the basins to the lakes.

Soto and Stockner (1996), comparing Canadian and Araucanian lakes, emphasized the extremely low nitrate and TN concentrations in the Araucanian lakes, located on the western slope of the Andes Mountains. They suggested that high absorption by the humid non-coniferous evergreen forest dominated by *Nothofagus* spp. resulted in low export rates from the terrestrial environment to the lakes. Pedrozo *et al.* (1993) determined extremely low inorganic N concentrations in Patagonian streams draining forests of *Nothofagus* spp. Rainwater N concentrations were lower than the world average, interpreted by the authors to be the result of the remoteness of the study area and little cultural impact. In turn, Mazzarino *et al.* (1998a) reviewed the available information about nutrient cycling in terrestrial ecosystems of the Patagonia. They

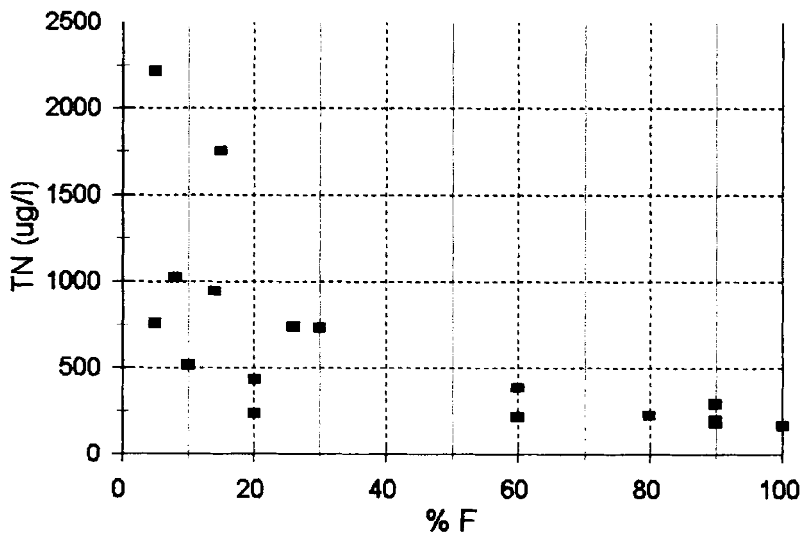

Figure 3. Relationship between percentage of forest cover in the basin (% F) and total nitrogen (μg/l).

reported that senescent leaves showed lower N concentration in *Nothofagus* spp. and grasses than in shrubs. *Nothofagus* spp. and grasses were very efficient in avoiding N losses from senescent leaves by resorption mechanisms. Higher N concentration and lower C/N ratios in senescent leaves and litter suggest faster decomposition and higher flushing rates from the land to the lakes in the shrub areas.

The observed correlation between TP and TN concentrations and the ratio between basin and lake surface indicated that the nutrient load increases as the watershed area increased. Deep volcanic ash deposits are very common within the Andean Patagonia, and in areas of high moisture such deposits formed soils of the andisol type, characterized by abundant complexes of organic matter and amorphous allophanous colloidal matter with high Al content (Colmet Daage *et al.* 1995). Volcanic ash derived soils are known for high P binding capacity (Poudel and West 1999). The high water retention of these soils determines that its geographic distribution is coincident with that of the *Nothofagus* spp. forest.

Eastward, with increasing aridity, mollisols and aridisols (Del Valle 1998) become dominant in the Patagonia Plateau. Because there is a close relationship between climate, soil, and vegetation, the percentage of forest cover in each basin indicates not only the dominant vegetation but also precipitation and edaphic patterns. Colmet Daage *et al.* (1995) reported large variations in soil properties along the andisol-mollisol ecotone in two nearby sites. Mazzarino *et al.* (1998b) reported that an andisol contained higher TP concentration but lower extractable P (assumed to represent soil available P) than a nearby mollisol. The former also showed seven times larger P retention capacity than the later. Comparatively low TP concentrations in the Andean lakes seem to be related to the high P retention of the prevailing allophanic soils.

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LITERATURE CITED

Andersen, J. 1979. An ignition method for determination of total phosphorus in lake sediments. Water Research 10: 329-331.

APHA, 1998. Standard methods for the examination of water and waste-water. American Public Health Association, Washington, 1193 p.

Baigún, C. and M. Marinone. 1995. Cold-temperate lakes of South America: do the fit Northern hemisphere models? Archiv fur Hydrobiologie 135: 23-51.

Colmet Daage, F., M., Lanciotti, and A. Marcolini. 1995. Importancia forestal de los suelos volcanicos de la Patagonia Norte y Central. INTA Bariloche, 29 p.

Del Valle, H. 1998. Patagonian soils: a regional synthesis. Ecología Austral 8: 103-123.

Drago, E. and R. Quirós. 1996. The hydrochemistry of the inland waters of Argentina: a review. International Journal of Salt Lake Research 4: 315-325.

Hutchinson, G. 1957. A treatise on limnology. 1. Geography, physics, and chemistry. John Wiley and Sons. New York, 1015 p.

Iglesias de Cuello, A. 1982. Cuencas salinas y espejos de agua. In: Chiozza, E and R. Figueira (eds.): Atlas físico de la República Argentina. Vol.2. Centro Editor de América Latina, Buenos Aires, 382-391.

Iriondo, M. 1989. Quaternary lakes of Argentina. Palaeogeography, Palaeoclimatology, Palaeoccology 70: 81-88.

Marcolini, A., C. Lopez, and M. Lanciotti. 1988. Características de los suelos derivados de cenizas volcánicas de la Cordillera de los Andes y precordillera del norte de la Patagonia. INTA: Informe Técnico s/n: 1-39.

Mazzarino, M., M. Bertiller, T. Schlichter, and M. Gobbi. 1998a. Nutrient cycling in Patagonian ecosystems. Ecología Austral 8: 167-181.

Mazzarino, M., F. Laos, P. Satti, and S. Moyano. 1998b. Agronomic and environmental aspects of utilization of organic residues in soils of the Andean-Patagonian Region. Soil Science and Plant Nutrition. 44: 105-113.

OECD. 1982. Eutrophication of waters: monitoring, assessment and control. OECD. Paris, 156 p

Pedrozo, F., S. Chillrud, P. Temporetti, and M. Diaz. 1993. Chemical composition and nutrient limitation in rivers and lakes of northern Patagonian Andes (39.5-42° S; 71° W) (Rep. Argentina). Proceedings of the 25th Congress of the International Association of Theoretical and Applied Limnology 25: 207-214

Poudel, D. and L.West. 1999. Soil development and fertility characteristics of a volcanic slope in Mindanao, the Philippines. Journal of the American Society of Soil Science 63: 1258-1273

Quirós, R. 1988. Relationships between air temperature, depth, nutrients and chlorophyll in 103 Argentinean lakes. Proceedings of the 23rd Congress of the International Association of Theoretical and Applied Limnology 23: 647-658

Quirós, R. and E. Drago. 1999. The environmental state of Argentinean lakes: an overview. Lakes and Reservoirs: Research and Management 4: 55-64

Ryding, S. and W. Rast. 1992. El control de la eutrofización en lagos y pantanos. UNESCO. Ediciones Pirámide. Madrid. 375 p.

Sokal, R. and F. Rohlf, 1979. Biometría. Principios y métodos estadísticos en la investigación biológica. H. Blume, Madrid, 832 p.

Soto, D. and J. Stockner. 1996. The temperate rainforest lakes of Chile and Canada: comparative ecology and sensitivity to anthropocentric change. In: J. Lawford, R. Alaback and C. Fuentes (eds): High latitude rain forest of the west coast of the Americas. Climate, hydrology, ecology and conservation. Springer, New York, Ecological Studies, 266-280.

Vollenweider, R. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Memorie dell'Istituto Italiano di Idrobiologia 33: 53-83.

Wurstbaugh, W., W. Vincent, R. Alfaro Tapia, C. Vincent, and P. Richerson. 1985. Nutrient limitation of algal growth and nitrogen fixation in a tropical alpine lake, Lake Titicaca (Peru/Bolivia). Freshwater Biology 15: 185-195.

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